

Our Docket No.: 96790P440
Express Mail No.: EV339905907US

UTILITY APPLICATION FOR UNITED STATES PATENT
FOR
ELECTROMAGNETIC FLOWMETER

Inventor(s):
Tomoshige Yamamoto

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN LLP
12400 Wilshire Boulevard, Seventh Floor
Los Angeles, California 90025
Telephone: (310) 207-3800

Specification

Title of the Invention

Electromagnetic Flowmeter

5 Background of the Invention

The present invention relates to an electromagnetic flowmeter which measures the flow rate of a fluid to be measured, which flows through a measuring pipe and, more particularly, to an exciting 10 method and signal processing method capable of realizing accurate flow rate measurement.

An electromagnetic flowmeter measures the flow rate of a conductive fluid to be measured, which flows through a measuring pipe, by converting the flow rate 15 into an electrical signal by using electromagnetic induction. Fig. 11 shows the arrangement of a conventional electromagnetic flowmeter.

This electromagnetic flowmeter comprises a measuring pipe 11 through which a fluid to be measured 20 flows and a pair of electrodes 12a and 12b which oppose each other in the measuring pipe 11 to be perpendicular to both the magnetic field applied to the fluid to be measured and an axis PAX of the measuring pipe 11 and also come into contact with the fluid to be measured. 25 The electrodes 12a and 12b detect an electromotive force generated by the magnetic field and the flow of the fluid to be measured.

The electromagnetic flowmeter also comprises an exciting coil 13 which applies, to the fluid to be measured, a magnetic field perpendicular to both the measuring pipe axis PAX and an electrode axis EAX that 5 connects the electrodes 12a and 12b, a signal conversion section 15 which detects the electromotive force between the electrodes 12a and 12b, and a flow rate output section 16 which calculates the flow rate of the fluid to be measured from the interelectrode electromotive 10 force detected by the signal conversion section 15.

In the electromagnetic flowmeter shown in Fig. 11, a plane PLN which includes the electrodes 12a and 12b and is perpendicular to the direction of the measuring pipe axis PAX is defined as a boundary in the 15 measuring pipe 11. At this time, symmetrical magnetic fields are applied to the fluid to be measured on both sides of the plane PLN, i.e., the boundary in the measuring pipe 11. The exciting coil 13 can be excited by a sine wave exciting method or a rectangular wave 20 exciting method (e.g., "A to Z of Flow Rate Measurement for Instrumentation Engineers" edited by Japan Measuring Instruments Federation, Kogyogijustusha, 1995, pp. 143-160).

The sine wave exciting method that uses a sine 25 wave as an exciting current for an exciting coil is readily affected by commercial frequency noise. However, this problem can be solved by a high-frequency

exciting method which uses an exciting current having a higher frequency.

The high-frequency exciting method is resistant to $1/f$ noise such as electrochemical noise or 5 spike noise. In addition, this method can improve the response (a characteristic which makes a flow rate signal quickly follow a change in flow rate).

However, the conventional sine wave exciting method is readily affected by in-phase component noise. 10 An example of in-phase component noise is a shift of the amplitude of a magnetic field applied to a fluid to be measured.

In the conventional electromagnetic flowmeter, when the amplitude of the exciting current supplied to 15 the exciting coil varies (shifts) due to a fluctuation in power supply voltage, and the amplitude of the magnetic field applied to the fluid to be measured shifts, the amplitude of the interelectrode electromotive force changes, resulting in a flow rate 20 measurement error due to the influence of shift. Such in-phase component noise cannot be removed even by the high-frequency exciting method.

To the contrary, the rectangular wave exciting method that uses a rectangular wave as an 25 exciting current to be supplied to an exciting coil is resistant to in-phase component noise.

In the rectangular wave exciting method,

however, the interelectrode electromotive force is detected when a change in magnetic field becomes zero. When the exciting current has a high frequency, the detector must have high performance.

5 Additionally, in the rectangular wave exciting method, when the exciting current has a high frequency, effects of the impedance of the exciting coil, the exciting current response, the magnetic field response, and an overcurrent loss in the core of the exciting coil
10 or measuring pipe cannot be neglected. It is difficult to maintain rectangular wave excitation.

As a result, in the rectangular wave exciting method, high-frequency excitation is difficult, and an increase in response to a change in flow rate or removal
15 of 1/f noise cannot be realized.

Summary of the Invention

It is an object of the present invention to provide an electromagnetic flowmeter which can remove in-phase component noise and correct any flow rate
20 measurement error and also realize high-frequency excitation.

In order to achieve the above object, according to the present invention, there is provided an electromagnetic flowmeter comprising a measuring pipe
25 through which a fluid to be measured flows, an electrode which is arranged in the measuring pipe and detects an electromotive force generated by a magnetic field

applied to the fluid and flow of the fluid, a first exciting coil which is arranged separately from a plane, which includes the electrode and is perpendicular to a direction of an axis of the measuring pipe, and applies 5 a first magnetic field having a first frequency to the fluid, a second exciting coil which is arranged on a side opposite to the first exciting coil with respect to the plane and applies, to the fluid, a second magnetic field obtained by amplitude-modulating a carrier having 10 the first frequency by a modulated wave having a second frequency, a power supply section which supplies an exciting current to the first exciting coil and the second exciting coil, a signal conversion section which separates a component of the first frequency from the 15 electromotive force detected by the electrode to obtain an amplitude, separates one of components of sum and difference frequencies of the first and second frequencies from the electromotive force to obtain an amplitude, and obtains a ratio of the amplitudes, and a 20 flow rate output section which calculates a flow rate of the fluid on the basis of the amplitude ratio obtained by the signal conversion section.

Brief Description of the Drawings

Fig. 1 is a view for explaining the basic 25 principle of an electromagnetic flowmeter according to the present invention;

Fig. 2 is a view showing an eddy current and

interelectrode electromotive force when the flow rate of a fluid to be measured is 0;

Fig. 3 is a view showing an eddy current and interelectrode electromotive force when the flow rate of 5 a fluid to be measured is not 0;

Fig. 4 is a block diagram showing the arrangement of an electromagnetic flowmeter according to the first embodiment of the present invention;

Fig. 5 is a graph showing the complex vector 10 of the frequency component of the carrier of the interelectrode electromotive force in the first embodiment of the present invention;

Fig. 6 is a graph showing the complex vector 15 of the frequency component of the sideband of the interelectrode electromotive force in the first embodiment of the present invention;

Fig. 7 is a graph showing the complex vector 20 of the frequency component of the sideband of an interelectrode electromotive force in the third embodiment of the present invention;

Fig. 8 is a view showing another example of the exciting coil arrangement in the electromagnetic flowmeter according to the present invention;

Fig. 9 is a sectional view showing an example 25 of the electrode used in the electromagnetic flowmeter according to the present invention;

Fig. 10 is a sectional view showing another

example of the electrode used in the electromagnetic flowmeter according to the present invention; and

Fig. 11 is a block diagram showing the arrangement of a conventional electromagnetic flowmeter.

5 Description of the Preferred Embodiments

[Basic Principle]

Before a description of the basic principle of the present invention, generally known basic mathematical knowledge will be described. A cosine wave 10 $A \cos(\omega t)$ and sine wave $B \sin(\omega t)$, which have the same frequency and different amplitudes, are synthesized into the following cosine wave. A and B are amplitudes, and ω is an angular frequency.

$$A \cos(\omega t) + B \sin(\omega t) = (A^2 + B^2)^{1/2} \cos(\omega t - \varepsilon) \quad 15$$

for $\varepsilon = \tan^{-1}(B/A)$... (1)

To analyze the synthesis of equation (1), it is convenient to map the cosine wave $A \cos(\omega t)$ and sine wave $B \sin(\omega t)$ onto a complex coordinate plane while plotting the amplitude A of the cosine wave $A \cos(\omega t)$ 20 along the real axis and the amplitude B of the sine wave $B \sin(\omega t)$ along the imaginary axis.

More specifically, on the complex coordinate plane, a distance $(A^2 + B^2)^{1/2}$ from the origin gives the amplitude of the synthetic wave, and an angle $\varepsilon = 25 \tan^{-1}(B/A)$ with respect to the real axis gives the phase difference between the synthetic wave and ωt .

In addition, on the complex coordinate plane,

the following relation holds

$$C_{\text{exp}}(j\epsilon) = C\cos(\epsilon) + jC\sin(\epsilon) \quad \dots(2)$$

Equation (2) is an expression of a complex vector. In equation (2), j is the imaginary number 5 unit, C is the length of the complex vector, and ϵ is the direction of the complex vector. Hence, to analyze the geometrical relationship on the complex coordinate plane, it is convenient to use conversion to a complex vector.

10 In the following description, to explain a behavior that is exhibited by an interelectrode electromotive force and the manner the present invention uses the behavior, mapping to the complex coordinate plane and geometrical analysis using a complex vector 15 are employed.

First, an interelectrode electromotive force which is irrelevant to the flow rate (flow velocity) of a fluid to be measured per unit time will be described. As shown in Fig. 1, an electromagnetic flowmeter 20 comprises a measuring pipe 1 through which a fluid to be measured flows and a pair of electrodes 2a and 2b which oppose each other in the measuring pipe 1 to be perpendicular to both the magnetic field applied to the fluid to be measured and an axis PAX of the measuring 25 pipe 1 and also come into contact with the fluid to be measured. The electrodes 2a and 2b detect an electromotive force generated by the magnetic field and

the flow of the fluid to be measured.

The electromagnetic flowmeter also comprises a first exciting coil 3a and second exciting coil 3b. In the electromagnetic flowmeter, a plane PLN which 5 includes the electrodes 2a and 2b and is perpendicular to the direction of the measuring pipe axis PAX is defined as a boundary in the measuring pipe 1. At this time, the first exciting coil 3a and second exciting coil 3b apply asymmetrical magnetic fields to the fluid 10 to be measured on both sides of the plane PLN, i.e., the boundary in the measuring pipe 1.

Of the magnetic field generated from the first exciting coil 3a, a magnetic field component (magnetic flux density) B_1 which is perpendicular to both an 15 electrode axis EAX that connects the electrodes 2a and 2b and the measuring pipe axis PAX on the electrode axis EAX, and of the magnetic field generated from the second exciting coil 3b, a magnetic field component (magnetic flux density) B_2 which is perpendicular to both the 20 electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX are given by

$$B_1 = b_1 \cos(\omega_0 t - \theta_1) \quad \dots (3)$$

$$B_2 = b_2 \cos(\omega_0 t - \theta_2) \quad \dots (4)$$

In equations (3) and (4), b_1 and b_2 are the 25 amplitudes, ω_0 is the angular frequency, and θ_1 and θ_2 are the phase differences (phase delays) from $\omega_0 t$. The magnetic flux density B_1 will be referred to as the

magnetic field B1, and the magnetic flux density B2 will be referred to as the magnetic field B2.

An electromotive force caused by a change in magnetic field is obtained by a time differential dB/dt 5 of the magnetic field. The magnetic fields B1 and B2 generated from the first exciting coil 3a and second exciting coil 3b are differentiated as follows.

$$dB1/dt = -b1\omega_0 \sin(\omega_0 t - \theta_1) \quad \dots (5)$$

$$dB2/dt = -b2\omega_0 \sin(\omega_0 t - \theta_2) \quad \dots (6)$$

10 When the flow rate of the fluid to be measured is 0, eddy currents generated by the magnetic fields B1 and B2 contain only components generated by a change in magnetic fields. An eddy current I_a by the magnetic field B1 and eddy current I_b by the magnetic field B2 15 have directions as shown in Fig. 2.

Hence, in the plane that includes the electrode axis EAX and measuring pipe axis PAX, an interelectrode electromotive force E_a that is generated by a change in magnetic field B1 and is irrelevant to 20 the flow rate (flow velocity) and an interelectrode electromotive force E_b that is generated by a change in magnetic field B2 and is irrelevant to the flow rate (flow velocity) have opposite directions, as shown in Fig. 2.

25 At this time, a total interelectrode electromotive force E obtained by adding the interelectrode electromotive forces E_a and E_b

corresponds to a value obtained by calculating the difference between the time differentials $dB1/dt$ and $dB2/dt$ of the magnetic fields and multiplying the difference by a coefficient k (a complex number related 5 to the conductivity and dielectric constant of the fluid to be measured and the structure of the measuring pipe 1).

$$E = k\{-b2\omega_0\sin(\omega_0t - \theta_2) + b1\omega_0\sin(\omega_0t - \theta_1)\} \dots (7)$$

10 Equation (7) can be rewritten to

$$\begin{aligned} E &= -kb2\omega_0\sin(\omega_0t)\cos(-\theta_2) \\ &\quad - kb2\omega_0\cos(\omega_0t)\sin(-\theta_2) \\ &\quad + kb1\omega_0\sin(\omega_0t)\cos(-\theta_1) \\ &\quad + kb1\omega_0\cos(\omega_0t)\sin(-\theta_1) \\ 15 &= \{-b2\sin(-\theta_2) \\ &\quad + b1\sin(-\theta_1)\}\omega_0k\cos(\omega_0t) \\ &\quad + \{-b2\cos(-\theta_2) \\ &\quad + b1\cos(-\theta_1)\}\omega_0k\sin(\omega_0t) \end{aligned} \dots (8)$$

20 When equation (8) is mapped onto a complex coordinate plane based on ω_0t , a real axis component Ex and imaginary axis component Ey are given by

$$Ex = \{-b2\sin(-\theta_2) + b1\sin(-\theta_1)\}\omega_0k \dots (9)$$

$$Ey = \{-b2\cos(-\theta_2) + b1\cos(-\theta_1)\}\omega_0k \dots (10)$$

25 Ex and Ey in equations (9) and (10) are rewritten to

$$Ex = \{-b2\sin(-\theta_2) + b1\sin(-\theta_1)\}\omega_0k$$

$$\begin{aligned}
&= \{-b_2 \cos(\pi/2 + \theta_2) + b_1 \cos(\pi/2 + \theta_1)\} \omega_0 k \\
&= \{b_2 \cos(-\pi/2 + \theta_2) + b_1 \cos(\pi/2 + \theta_1)\} \omega_0 k
\end{aligned}
\quad \dots (11)$$

$$\begin{aligned}
5 \quad E_y &= \{-b_2 \cos(-\theta_2) + b_1 \cos(-\theta_1)\} \omega_0 k \\
&= \{-b_2 \sin(\pi/2 + \theta_2) + b_1 \sin(\pi/2 + \theta_1)\} \omega_0 k \\
&= \{b_2 \sin(-\pi/2 + \theta_2) + b_1 \sin(\pi/2 + \theta_1)\} \omega_0 k
\end{aligned}
\quad \dots (12)$$

to obtain a complex vector E_c given by

$$\begin{aligned}
10 \quad E_c &= E_x + jE_y \\
&= \{b_2 \cos(-\pi/2 + \theta_2) \\
&\quad + b_1 \cos(\pi/2 + \theta_1)\} \omega_0 k \\
&\quad + j\{b_2 \sin(-\pi/2 + \theta_2) \\
&\quad + b_1 \sin(\pi/2 + \theta_1)\} \omega_0 k \\
&= \{b_1 \cos(\pi/2 + \theta_1) \\
&\quad + j b_1 \sin(\pi/2 + \theta_1)\} \omega_0 k \\
&\quad + \{b_2 \cos(-\pi/2 + \theta_2) \\
&\quad + j b_2 \sin(-\pi/2 + \theta_2)\} \omega_0 k \\
&= b_1 \omega_0 k \exp\{j(\pi/2 + \theta_1)\} \\
&\quad + b_2 \omega_0 k \exp\{j(-\pi/2 + \theta_2)\}
\end{aligned}
\quad \dots (13)$$

20

The above-described coefficient k can be converted into a complex vector given by

$$\begin{aligned}
k &= r k \cos(\theta_00) + j r k \sin(\theta_00) \\
&= r k \exp(j \theta_00)
\end{aligned}
\quad \dots (14)$$

25 In equation (14), $r k$ is a proportional coefficient, and θ_00 is the angle of the vector k with respect to the real axis. The angle θ_00 changes in

accordance with a delay of the magnetic field with respect to the exciting current or a change in conductivity of the fluid. The change in angle θ_{00} is a flow rate measurement error.

5 When equation (14) is substituted into equation (13), the interelectrode electromotive force E_C (an interelectrode electromotive force which is caused only by a time-rate change in magnetic field and is irrelevant to the flow velocity) converted into the 10 complex vector is given by

$$\begin{aligned} E_C &= b_1 \omega_0 k \exp(j(\pi/2 + \theta_1)) \\ &\quad + b_2 \omega_0 k \exp(j(-\pi/2 + \theta_2)) \\ &= b_1 \omega_0 r k \exp(j(\pi/2 + \theta_1 + \theta_{00})) \\ &\quad + b_2 \omega_0 r k \exp(j(-\pi/2 + \theta_2 + \theta_{00})) \end{aligned} \quad \dots (15)$$

15 In equation (15), $b_1 \omega_0 r k \exp\{j(\pi/2 + \theta_1 + \theta_{00})\}$ is a complex vector whose length is $b_1 \omega_0 r k$ and angle from the real axis is $\pi/2 + \theta_1 + \theta_{00}$, and $b_2 \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ is a complex vector whose length is $b_2 \omega_0 r k$ and angle from the real axis is $-\pi/2 + \theta_2 + \theta_{00}$.

20 The interelectrode electromotive force caused by the flow rate (flow velocity) of the fluid to be measured will be described next. When the flow velocity 25 of the fluid to be measured is V ($V \neq 0$), eddy currents by the magnetic fields B_1 and B_2 respectively contain components $V \times B_1$ and $V \times B_2$ caused by the flow

velocity in addition to the eddy current components I_a and I_b when the flow velocity is 0. For this reason, an eddy current I_a' by the magnetic field B_1 and an eddy current I_b' by the magnetic field B_2 have directions as
5 shown in Fig. 3.

Hence, an interelectrode electromotive force E_a' generated by the flow velocity V of the fluid to be measured and the magnetic field B_1 and an interelectrode electromotive force E_b' generated by the flow velocity V
10 and the magnetic field B_2 have the same direction.

At this time, a total interelectrode electromotive force E_v obtain by adding the interelectrode electromotive forces E_a' and E_b' generated by the flow velocity corresponds to the sum of
15 a value obtained by multiplying the magnetic field B_1 by a coefficient k_v (a complex number related to the flow velocity V , the conductivity and dielectric constant of the fluid to be measured, and the structure of the measuring pipe 1) and a value obtained by multiplying
20 the magnetic field B_2 by the coefficient k_v .

$$E_v = k_v \{ b_1 \cos(\omega_0 t - \theta_1) + b_2 \cos(\omega_0 t - \theta_2) \} \quad \dots (16)$$

When the term of sin and the term of cos of equation (16) are expanded, we obtain

25
$$E_v = k_v b_1 \cos(\omega_0 t) \cos(-\theta_1) - k_v b_1 \sin(\omega_0 t) \sin(-\theta_1) + k_v b_2 \cos(\omega_0 t) \cos(-\theta_2)$$

$$\begin{aligned}
& - kvb2 \sin(\omega_0 t) \sin(-\theta_2) \\
= & \{b1 \cos(-\theta_1) \\
& + b2 \cos(-\theta_2)\} kvc \cos(\omega_0 t) \\
& + \{-b1 \sin(-\theta_1) \\
& - b2 \sin(-\theta_2)\} kvs \sin(\omega_0 t) \quad \dots (17)
\end{aligned}$$

When equation (17) is mapped onto the complex coordinate plane based on $\omega_0 t$, a real axis component E_{Vx} and imaginary axis component E_{Vy} are given by

$$E_{Vx} = \{b1 \cos(-\theta_1) + b2 \cos(-\theta_2)\} kv \quad \dots (18)$$

$$10 \quad E_{Vy} = \{-b1 \sin(-\theta_1) - b2 \sin(-\theta_2)\} kv \quad \dots (19)$$

Equations (18) and (19) are transformed into a complex vector E_{Vc} .

$$\begin{aligned}
E_{Vx} & = \{b1 \cos(-\theta_1) + b2 \cos(-\theta_2)\} kv \\
& = \{b1 \cos(\theta_1) + b2 \cos(\theta_2)\} kv \quad \dots (20)
\end{aligned}$$

$$\begin{aligned}
15 \quad E_{Vy} & = \{-b1 \sin(-\theta_1) - b2 \sin(-\theta_2)\} kv \\
& = \{b1 \sin(\theta_1) + b2 \sin(\theta_2)\} kv \quad \dots (21)
\end{aligned}$$

$$\begin{aligned}
E_{Vc} & = E_{Vx} + j E_{Vy} \\
& = \{b1 \cos(\theta_1) + b2 \cos(\theta_2)\} kv \\
& + j \{b1 \sin(\theta_1) + b2 \sin(\theta_2)\} kv \\
& = \{b1 \cos(\theta_1) + j b1 \sin(\theta_1)\} kv \\
& + \{b2 \cos(\theta_2) + j b2 \sin(\theta_2)\} kv \\
& = b1 kv \exp(j\theta_1) + b2 kv \exp(j\theta_2) \\
& \quad \dots (22)
\end{aligned}$$

25 The above-described coefficient kv is transformed to a complex vector.

$$kv = rkvc \cos(\theta_{01}) + j rkvs \sin(\theta_{01})$$

$$= \text{rkvexp}(j\theta_{01}) \quad \dots (23)$$

In equation (23), rkv is a proportional coefficient, θ_{01} is the angle of the vector kv with respect to the real axis. In this case, rkv corresponds to a value obtained by multiplying the proportional coefficient rk (equation (14)) by the flow velocity V and a proportional coefficient γ , so $v = V\gamma$. That is,

$$\text{rkv} = \text{rk}V\gamma \quad \dots (24)$$

When equation (23) is substituted into equation (22), the interelectrode electromotive force E_{vc} converted into complex coordinates is obtained as

$$\begin{aligned} E_{vc} &= b1kvexp(j\theta_1) + b2kvexp(j\theta_2) \\ &= b1rkvexp\{j(\theta_1 + \theta_{01})\} \\ &\quad + b2rkvexp\{j(\theta_2 + \theta_{01})\} \end{aligned} \quad \dots (25)$$

In equation (25), $b1rkvexp\{j(\theta_1 + \theta_{01})\}$ is a complex vector whose length is $b1rkv$ and angle from the real axis is $\theta_1 + \theta_{01}$, and $b2rkvexp\{j(\theta_2 + \theta_{01})\}$ is a complex vector whose length is $b2rkv$ and angle from the real axis is $\theta_2 + \theta_{01}$.

From equations (15) and (25), a total interelectrode electromotive force E_{ac} obtained by adding the interelectrode electromotive force E_c generated by a time-rate change in magnetic field and the interelectrode electromotive force E_{vc} generated by the flow velocity of the fluid is given by

$$\begin{aligned} E_{ac} &= E_c + E_{vc} \\ &= b1\omega_0rkexp\{j(\pi/2 + \theta_1 + \theta_{00})\} \end{aligned}$$

$$\begin{aligned}
& + b2\omega_0 rk \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
& + b1rk \exp\{j(\theta_1 + \theta_01)\} \\
& + b2rk \exp\{j(\theta_2 + \theta_01)\} \quad \dots (26)
\end{aligned}$$

As is apparent from equation (26), the

5 interelectrode electromotive force Eac is described by
the four complex vectors $b1\omega_0 rk \exp\{j(\pi/2 + \theta_1 + \theta_00)\}$, $b2\omega_0 rk \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$, $b1rk \exp\{j(\theta_1 + \theta_01)\}$, and $b2rk \exp\{j(\theta_2 + \theta_01)\}$.

10 The length of a synthetic vector obtained by
synthesizing the four complex vectors represents the
amplitude of the output (interelectrode electromotive
force Eac), and an angle ϕ of the synthetic vector
represents the phase difference (phase delay) of the
interelectrode electromotive force Eac from the phase ω
15 $\omega_0 t$ of the input (exciting current).

In the present invention, the carrier of an
angular frequency ω_0 is amplitude-, phase-, or
frequency-modulated by the modulated wave of an angular
frequency ω_2 to obtain an exciting current. The
20 exciting current is supplied to the first and second
exciting coils 3a and 3b to apply asymmetrical magnetic
fields to the fluid to be measured on both sides of the
plane PLN, i.e., the boundary in the measuring pipe 1.

Accordingly, a plurality of frequency
25 components ω_0 , $\omega_0 + \xi\omega_2$, and $\omega_0 - \xi\omega_2$ (ξ is an
integer ($\xi \geq 1$)); for amplitude modulation, only $\xi = 1$)
are generated in the interelectrode electromotive force

Each. From two of these frequency components, an asymmetrical exciting characteristic parameter (amplitude ratio or phase difference) is obtained, which depends on the flow rate of the fluid and does not 5 depend on the variation in delay (θ_{00}) of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field. On the basis of the asymmetrical exciting characteristic parameter, a flow rate measurement error due to the variation in 10 delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field is automatically corrected. This is the basic technical idea of the present invention.

Accordingly, in-phase component noise is 15 removed so that the rectangular wave exciting method need not be used, and the sine wave exciting method can be used.

[First Embodiment]

An embodiment of the present invention will 20 be described below in detail. Fig. 4 shows the arrangement of an electromagnetic flowmeter according to the first embodiment of the present invention. The same reference numerals as in Fig. 1 denote the same components in Fig. 4.

The electromagnetic flowmeter according to 25 this embodiment comprises a measuring pipe 1, electrodes 2a and 2b, first and second exciting coils 3a and 3b,

and a power supply section 4 which supplies a first exciting current to the first exciting coil 3a and a second exciting current to the second exciting coil 3b.

The electromagnetic flowmeter also comprises a 5 signal conversion section 5 and flow rate output section 6. The signal conversion section 5 obtains an amplitude by separating a component having an angular frequency ω_0 from an electromotive force detected by the electrodes 2a and 2b, obtains an amplitude by separating a 10 component having a sum frequency ($\omega_0 + \omega_2$) or a difference frequency ($\omega_0 - \omega_2$) of the angular frequency ω_0 and an angular frequency ω_2 from the electromotive force, and obtains the ratio of these amplitudes. The flow rate output section 6 calculates 15 the flow rate of a fluid to be measured on the basis of the amplitude ratio obtained by the signal conversion section 5.

The first exciting coil 3a is arranged downstream of a plane PLN at a position separated from 20 it by an offset distance d_1 . The second exciting coil 3b is arranged upstream of the plane PLN at a position separated from it by an offset distance d_2 . That is, the second exciting coil 3b is arranged on the opposite side of the first exciting coil 3a with respect to the 25 plane PLN

The power supply section 4 supplies a first sine wave exciting current having the first angular

frequency ω_0 to the first exciting coil 3a. In this embodiment, $b_1 = b$ and $\theta_1 = 0$ in equation (3). Of the magnetic field generated from the first exciting coil 3a when the first exciting current is supplied from the 5 power supply section 4, a magnetic field component B_1 that is perpendicular to both an electrode axis EAX and a measuring pipe axis PAX on the electrode axis EAX is given by

$$B_1 = b \cos(\omega_0 t) \quad \dots (27)$$

10 The power supply section 4 also supplies a second exciting current to the second exciting coil 3b. The second exciting current is obtained by amplitude-modulating a sine wave carrier having the same angular frequency ω_0 as that of the carrier component 15 of the first exciting current and a predetermined phase difference θ_2 by using a modulated sine wave having the second angular frequency ω_2 .

Of the magnetic field generated from the second exciting coil 3b when the second exciting current 20 is supplied from the power supply section 4, an amplitude b_2 of a magnetic field component B_2 that is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX is given by

$$b_2 = b \{ 1 + m_i \cos(\omega_2 t) \} \quad \dots (28)$$

In equation (28), m_i is an amplitude modulation index. From equations (4) and (28), the

magnetic field B_2 is given by

$$B_2 = b\{1 + m_a \cos(\omega_2 t)\} \cos(\omega_0 t - \theta_2) \quad \dots (29)$$

In equation (26), $b_1 = b$, $\theta_1 = 0$, and $\theta_{01} = \theta_{00}$. When the magnetic fields B_1 and B_2 are given by equations (27) and (29), we obtain

$$\begin{aligned} E_{AC} &= E_C + E_{VC} \\ &= b\omega_0 r_k \exp\{j(\pi/2 + \theta_{00})\} \\ &\quad + b\{1 + m_a \cos(\omega_2 t)\} \omega_0 r_k \exp\{j(-\pi/2 \\ &\quad + \theta_2 + \theta_{00})\} + b r_k v \exp\{j(\theta_{00})\} \\ &\quad + b\{1 + m_a \cos(\omega_2 t)\} r_k v \exp\{j(\theta_2 + \theta_{00})\} \\ 10 &= b\omega_0 r_k \exp\{j(\pi/2 + \theta_{00})\} \\ &\quad + b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\} \\ &\quad + b r_k v \exp\{j(\theta_{00})\} \\ &\quad + b r_k v \exp\{j(\theta_2 + \theta_{00})\} \\ 15 &\quad + m_a \cos(\omega_2 t) b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\} \\ &\quad + m_a \cos(\omega_2 t) b r_k v \exp\{j(\theta_2 + \theta_{00})\} \\ &\quad \dots (30) \end{aligned}$$

Four vectors on the right-hand side of equation (30), i.e., $b\omega_0 r_k \exp\{j(\pi/2 + \theta_{00})\}$ as the first term, $b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ as the second term, $b r_k v \exp\{j(\theta_{00})\}$ as the third term, and $b r_k v \exp\{j(\theta_2 + \theta_{00})\}$ as the fourth term correspond to fundamental vectors obtained when no amplitude modulation is done.

25 The vector as the fifth term on the right-hand side of equation (30), i.e., $m_a \cos(\omega_2 t) b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ can be rewritten to $b\omega_0 r_k m_a \cos(\omega_0 t - (-\pi$

$\theta_2 + \theta_000 \cos(\omega_2 t)$ as time expression. This time expression can further be rewritten to

$$\begin{aligned}
 & b\omega_0 r k m_a \cos(\omega_0 t) \\
 & \quad - (-\pi/2 + \theta_2 + \theta_000) \cos(\omega_2 t) \\
 5 & = (1/2) b\omega_0 r k m_a [\cos(\omega_0 t \\
 & \quad - (-\pi/2 + \theta_2 + \theta_000) + \omega_2 t) \\
 & \quad + \cos(\omega_0 t - (-\pi/2 + \theta_2 + \theta_000) - \omega_2 t)] \\
 & = (1/2) b\omega_0 r k m_a \cos((\omega_0 + \omega_2)t \\
 & \quad - (-\pi/2 + \theta_2 + \theta_000)) \\
 10 & \quad + (1/2) b\omega_0 r k m_a \cos((\omega_0 - \omega_2)t \\
 & \quad - (-\pi/2 + \theta_2 + \theta_000)) \\
 & \quad \dots (31)
 \end{aligned}$$

As is apparent from equation (31), the fifth term on the right-hand side of equation (30) forms a vector $(1/2) b\omega_0 r k m_a \exp(j(-\pi/2 + \theta_2 + \theta_000))$ on each of a complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and a complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

The vector as the sixth term on the right-hand side of equation (30), i.e., $m_a \cos(\omega_2 t) b r k v \exp(j(\theta_2 + \theta_000))$ can be rewritten to $b r k v m_a \cos(\omega_0 t - (\theta_2 + \theta_000)) \cos(\omega_2 t)$ as time expression. This time expression can further be rewritten to

$$\begin{aligned}
 & b r k v m_a \cos(\omega_0 t - (\theta_2 + \theta_000)) \cos(\omega_2 t) \\
 25 & = (1/2) b r k v m_a [\cos(\omega_0 t - (\theta_2 + \theta_000) + \omega_2 t) \\
 & \quad + \cos(\omega_0 t - (\theta_2 + \theta_000) - \omega_2 t)] \\
 & = (1/2) b r k v m_a \cos((\omega_0 + \omega_2)t - (\theta_2 + \theta_000))
 \end{aligned}$$

$$\begin{aligned}
& + 1/2 \text{brkv}_a \cos\{(\omega_0 - \omega_2)t \\
& - (\theta_2 + \theta_00)\}
\end{aligned}
\quad \dots (32)$$

As is apparent from equation (32), the sixth
5 term on the right-hand side of equation (30) forms a
vector $(1/2)\text{brkv}_a \exp\{j(\theta_2 + \theta_00)\}$ on each of the
complex plane based on the angular frequency $(\omega_0 + \omega_2)$
and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

10 As is apparent from the above description, the
fifth and sixth terms on the right-hand side of equation
(30) form a complex vector E_{am} on each of the complex
plane based on the angular frequency $(\omega_0 + \omega_2)$ and the
complex plane based on the angular frequency $(\omega_0 - \omega_2)$.
15 The complex vector E_{am} is given by

$$\begin{aligned}
E_{am} = & (1/2)b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
& + (1/2)\text{brkv}_a \exp\{j(\theta_2 + \theta_00)\}
\end{aligned}
\quad \dots (33)$$

In addition, the first to fourth terms on the
20 right-hand side of equation (30) form a complex vector
 E_{or} on a complex plane based on the angular frequency ω_0 .
The complex vector E_{or} is given by

$$\begin{aligned}
E_{or} = & b\omega_0 r_k \exp\{j(\pi/2 + \theta_00)\} \\
& + b\omega_0 r_k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
& + \text{brkv} \exp\{j(\theta_00)\} \\
& + \text{brkv} \exp\{j(\theta_2 + \theta_00)\}
\end{aligned}
\quad \dots (34)$$

Fig. 5 shows the complex vector E_{or} formed on the complex plane based on the angular frequency ω_0 of the carrier. Fig. 6 shows the complex vector E_{am} formed on the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ of the sideband.

The complex vector E_{am} is the synthetic vector of two complex vectors $(1/2)b\omega_0rk_{m_a}\exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ and $(1/2)brk_{v_m}\exp\{j(\theta_2 + \theta_{00})\}$, which are perpendicular to each other. This synthetic vector only rotates about an origin A of the complex coordinate system shown in Fig. 6 as the angle θ_{00} changes. Hence, the synthetic vector has a predetermined magnitude independently of the change in angle θ_{00} . The magnitude $|E_{am}|$ of the complex vector E_{am} is given by

$$\begin{aligned} |E_{am}| &= \left[\left\{ (1/2)b\omega_0rk_{m_a} \right\}^2 \right. \\ &\quad \left. + \left\{ (1/2)brk_{v_m} \right\}^2 \right]^{1/2} \\ &= (1/2)brk_{v_m} \{ \omega_0^2 + v^2 \}^{1/2} \end{aligned} \quad \dots (35)$$

The complex vector E_{or} is a synthetic vector of four complex vectors $b\omega_0rk\exp\{j(\pi/2 + \theta_{00})\}$, $b\omega_0rk\exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$, $brkv\exp\{j(\theta_{00})\}$, and $brkv\exp\{j(\theta_2 + \theta_{00})\}$, which form two isosceles triangles $\triangle ABC$ and $\triangle CDE$, as shown in Fig. 5. This synthetic vector only rotates about an origin B of the complex coordinate system shown as the angle θ_{00} changes. Hence, the synthetic vector has a

predetermined magnitude independently of the change in angle θ_{00} . When the bases of the isosceles triangles $\triangle ABC$ and $\triangle CDE$ are synthesized, the magnitude $|E_{or}|$ of the complex vector E_{or} is given by

$$\begin{aligned}
 5 \quad |E_{or}| &= 2b\omega_0 r k \sin(\theta/2) \\
 &\quad + 2brk v \cos(\theta/2) \\
 &= 2brk\{\omega_0 \sin(\theta/2) + v \cos(\theta/2)\} \\
 &\quad \dots (36)
 \end{aligned}$$

10 A ratio R_{am} of the magnitude $|E_{or}|$ of the complex vector E_{or} to the magnitude $|E_{am}|$ of the complex vector E_{am} is given by

$$\begin{aligned}
 R_{am} &= |E_{or}| / |E_{am}| \\
 &= [2brk\{\omega_0 \sin(\theta/2) + v \cos(\theta/2)\}] \\
 &\quad / \{(1/2)brk m_a \{\omega_0^2 + v^2\}^{1/2}\} \\
 15 \quad &= [4\{\omega_0 \sin(\theta/2) + v \cos(\theta/2)\}] \\
 &\quad / \{m_a \{\omega_0^2 + v^2\}^{1/2}\} \\
 &\quad \dots (37)
 \end{aligned}$$

The angular frequency ω_0 , phase difference θ , and amplitude modulation index m_a are irrelevant to the angle θ_{00} or the amplitude b of the magnetic field B_1 (the amplitude of the carrier component of the magnetic field B_2). Equation (37) that represents the ratio R_{am} has no term containing the angle θ_{00} or amplitude b .

25 Hence, even when the angle θ_{00} changes, or the amplitude b shifts, the ratio R_{am} does not change. When the magnitude $|E_{or}|$ of the complex vector E_{or} and

the magnitude $|E_{am}|$ of the complex vector E_{am} are obtained, and the flow rate is detected on the basis of the ratio R_{am} , a flow rate measurement error due to the variation in delay of the magnetic field with respect to 5 the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

To obtain the flow rate of the fluid to be measured, equation (37) is rewritten to

$$10 \quad v = \omega_0 \{ -8\sin(\theta_2) + R_{am} m_a^2 (16 - R_{am} m_a^2)^{1/2} \} / \{ 8 + 8\cos(\theta_2) - R_{am} m_a^2 \} \quad \dots (38)$$

From equation (24), equation (38) can be rewritten to

$$15 \quad v = \alpha \times \omega_0 \{ -8\sin(\theta_2) + R_{am} m_a^2 (16 - R_{am} m_a^2)^{1/2} \} / \{ 8 + 8\cos(\theta_2) - R_{am} m_a^2 \} \quad \dots (39)$$

for $\alpha = 1/\gamma$

where α (or γ) is a predetermined coefficient. The signal conversion section 5 detects the electromotive 20 force E_{ac} between the electrodes 2a and 2b and frequency-separates the detected interelectrode electromotive force E_{ac} by a filter. Accordingly, the amplitude of the component having the angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ (the magnitude $|E_{am}|$ of the 25 complex vector E_{am}) and the amplitude of the component having the angular frequency ω_0 (the magnitude $|E_{or}|$ of the complex vector E_{or}) are obtained.

The signal conversion section 5 calculates the ratio R_{AM} of the magnitudes $|E_{or}|$ to $|E_{am}|$.

The interelectrode electromotive force E_{AC} can also be frequency-separated even by using a bandpass 5 filter. Actually, when a comb-shaped digital filter called a comb filter is used, the interelectrode electromotive force can easily be separated into the three frequency components ω_0 , $(\omega_0 + \omega_2)$, and $(\omega_0 - \omega_2)$.

10 The flow rate output section 6 calculates a flow velocity V of the fluid to be measured, i.e., the flow rate per unit time by using equation (39) on the basis of the ratio R_{AM} obtained by the signal conversion section 5. With the above arrangement, in this 15 embodiment, the flow rate can be calculated while quickly and automatically canceling the flow rate measurement error so that accurate flow rate measurement can be executed.

[Second Embodiment]

20 The second embodiment of the present invention will be described next. The arrangement of an electromagnetic flowmeter according to this embodiment is the same as in the first embodiment and will be described with reference to Fig. 4. The operation of a 25 power supply section 4 according to this embodiment is the same as in the first embodiment. A magnetic field B_1 generated from a first exciting coil 3a when an

exciting current is supplied from the power supply section 4 is given by equation (27). A magnetic field B_2 generated from a second exciting coil 3b is given by equation (29). When $b_1 = b$, $\theta_1 = 0$, and $\theta_{01} = \theta_{00}$ in 5 equation (26), an interelectrode electromotive force E_{ac} is given by equation (30).

Four vectors that represent a component (complex vector E_{or}) having an angular frequency ω_0 of the interelectrode electromotive force E_{ac} have a 10 geometrical relationship as shown in Fig. 5 described in the first embodiment. Two vectors that represent a component (complex vector E_{am}) having an angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ have a geometrical relationship as shown in Fig. 6.

15 From Fig. 5, a phase difference ϕ_{or} between the complex vector E_{or} and the first exciting current supplied to the first exciting coil 3a is given by

$$\phi_{or} = \theta_2/2 + \theta_{00} \quad \dots(40)$$

From equation (40), an angle θ_{00} is given by 20

$$\theta_{00} = \phi_{or} - \theta_2/2 \quad \dots(41)$$

Let ϕ_{am} be the phase difference between the component having the angular frequency $(\omega_0 + \omega_2)$ of the interelectrode electromotive force E_{ac} and the component having the angular frequency $(\omega_0 + \omega_2)$ when 25 $\theta_2 = 0$ in the second exciting current supplied to the second exciting coil 3b or the phase difference between the component having the angular frequency $(\omega_0 - \omega_2)$

of the interelectrode electromotive force E_{ac} and the component having the angular frequency $(\omega_0 - \omega_2)$ when $\theta_2 = 0$ in the second exciting current.

In addition, let ϕ_x be the angle made by a vector $(1/2)b\omega_0rkm_a \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ as the first term on the right-hand side of equation (33) and a vector $(1/2)brkvm_a \exp\{j(\theta_2 + \theta_{00})\}$ as the second term on the right-hand side.

At this time, a relation given by equation 10 (42) holds between the phase difference ϕ_{am} and the angle ϕ_x as is apparent from Fig. 6. In the example shown in Fig. 6, however, the phase difference ϕ_{am} has a negative value.

$$\begin{aligned} \phi_x &= \pi/2 + \phi_{am} - \theta_{00} - \theta_2 \\ 15 &= \pi/2 + \phi_{am} - (\phi_{or} - \theta_2/2) - \theta_2 \\ &= \pi/2 + \phi_{am} - \phi_{or} - \theta_2/2 \end{aligned} \dots (42)$$

In addition, $\triangle ABC$ shown in Fig. 6, which is formed by the two complex vectors $(1/2)b\omega_0rkm_a \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$ and $(1/2)brkvm_a \exp\{j(\theta_2 + \theta_{00})\}$ and 20 their synthetic vector E_{am} , is a right triangle. Hence,

$$\begin{aligned} \tan \phi_x &= \{(1/2)brkvm_a\}/\{(1/2)b\omega_0rkm_a\} \\ &= v/\omega_0 \end{aligned} \dots (43)$$

Equation (43) can be rewritten to

$$v = \omega_0 \tan \phi_x = \omega_0 \tan\{\pi/2 + \phi_{am} - \phi_{or} - \theta_2/2\}$$

$$25 \dots (44)$$

From equation (24), equation (44) can be rewritten to

$$V = \alpha \times \omega_0 \tan(\pi/2 + \phi_{am} - \phi_{or} - \theta_2/2)$$

for $\alpha = 1/\gamma$... (45)

Equation (45) that represents a flow velocity V has no terms of the amplitude of the magnetic field B_1 (the amplitude of the carrier component of the magnetic field B_2) and angle θ_{00} . Hence, when the flow rate is detected on the basis of the phase differences ϕ_{am} and ϕ_{or} , a flow rate measurement error due to the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

A signal conversion section 5 frequency-separates the interelectrode electromotive force E_{ac} by using a filter, as in the first embodiment, to obtain the phase difference ϕ_{or} between the complex vector E_{or} and the first exciting current supplied to the first exciting coil 3a. The signal conversion section 5 also frequency-separates the second exciting current supplied to the second exciting coil 3b by using the filter to obtain the phase difference ϕ_{am} between the complex vector E_{am} and the component having the angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ of the second exciting current.

A flow rate output section 6 calculates the flow velocity V of the fluid to be measured by using equation (45) on the basis of the phase differences ϕ_{am}

and ϕ or obtained by the signal conversion section 5.

With the above arrangement, the same effect as in the first embodiment can be obtained.

Instead of using the component having the 5 angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ of the exciting current supplied to the second exciting coil 3b as the reference phase of the phase difference ϕ_{am} , the phase difference ϕ_{am} may be detected with reference to a timing when $\cos(\omega_2 t)$ becomes 1.0.

10 [Third Embodiment]

The third embodiment of the present invention will be described next. The arrangement of an electromagnetic flowmeter according to this embodiment is the same as in the first embodiment and will be 15 described with reference to Fig. 4. A power supply section 4 according to this embodiment supplies a first exciting current to a first exciting coil 3a. The first exciting current is obtained by amplitude-modulating a sine wave carrier having a first angular frequency ω_0 20 by a modulated sine wave having a second angular frequency ω_2 . Of the magnetic field generated from the first exciting coil 3a when the first exciting current is supplied from the power supply section 4, a magnetic field component B_1 which is perpendicular to both an 25 electrode axis EAX and a measuring pipe axis PAX on the electrode axis EAX has an amplitude b_1 given by

$$b_1 = b \{1 - m_a \cos(\omega_2 t)\} \quad \dots (46)$$

In this embodiment, $\theta_1 = 0$ in equation (3).

From equations (3) and (46), the magnetic field component B_1 is given by

$$B_1 = b\{1 - m_a \cos(\omega_2 t)\} \cos(\omega_0 t) \quad \dots (47)$$

5 The power supply section 4 also supplies a second exciting current to a second exciting coil 3b. The second exciting current is obtained by amplitude-modulating a sine wave carrier having the same angular frequency ω_0 as that of the carrier component 10 of the first exciting current and a predetermined phase difference θ_2 by a modulated sine wave having the same angular frequency ω_2 as that of the modulated wave component of the first exciting current and an opposite phase.

15 Of the magnetic field generated from the second exciting coil 3b when the second exciting current is supplied from the power supply section 4, a magnetic field component B_2 which is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on 20 the electrode axis EAX has an amplitude b_2 given by

$$b_2 = b\{1 + m_a \cos(\omega_2 t)\} \quad \dots (48)$$

From equations (4) and (48), the magnetic field component B_2 is given by

$$B_2 = b\{1 + m_a \cos(\omega_2 t)\} \cos(\omega_0 t - \theta_2) \quad \dots (49)$$

25 In equation (26), $\theta_1 = 0$, and $\theta_{01} = \theta_{00}$.

When the magnetic fields B_1 and B_2 are given by equations (47) and (49), we obtain

$$\begin{aligned}
E_{ac} &= E_c + E_{vc} \\
&= b\{1 - m_a \cos(\omega_2 t)\} \omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\
&\quad + b\{1 + m_a \cos(\omega_2 t)\} \omega_0 r k \exp\{j(-\pi/2 + \theta_2 \\
&\quad + \theta_00)\} \\
&\quad + b\{1 - m_a \cos(\omega_2 t)\} r k v \exp\{j(\theta_00)\} \\
&\quad + b\{1 + m_a \cos(\omega_2 t)\} r k v \exp\{j(\theta_2 + \theta_00)\} \\
&= b \omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\
&\quad + b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
&\quad + b r k v \exp\{j(\theta_00)\} \\
&\quad + b r k v \exp\{j(\theta_2 + \theta_00)\} \\
&\quad - m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\
&\quad - m_a \cos(\omega_2 t) b r k v \exp\{j(\theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b r k v \exp\{j(\theta_2 + \theta_00)\} \\
&= b \omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\
&\quad + b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
&\quad + b r k v \exp\{j(\theta_00)\} \\
&\quad + b r k v \exp\{j(\theta_2 + \theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(-\pi/2 + \theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b r k v \exp\{j(\pi + \theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\
&\quad + m_a \cos(\omega_2 t) b r k v \exp\{j(\theta_2 + \theta_00)\} \\
&\quad \dots \quad (50)
\end{aligned}$$

25 Four vectors on the right-hand side of
equation (50), i.e., $b \omega_0 r k \exp\{j(\pi/2 + \theta_00)\}$ as the
first term, $b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ as the
second term, $b r k v \exp\{j(\theta_00)\}$ as the third term, and

brkvexp{j(θ2 + θ00)} as the fourth term correspond to fundamental vectors obtained when no amplitude modulation is done.

The vector as the fifth term on the right-hand side of equation (50), i.e., $m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(-\pi/2 + \theta_00)\}$ can be rewritten to $b \omega_0 r k m_a \cos(\omega_0 t - (-\pi/2 + \theta_00)) \cos(\omega_2 t)$ as time expression. This time expression can further be rewritten to

$$\begin{aligned}
 & b \omega_0 r k m_a \cos(\omega_0 t - (-\pi/2 + \theta_00)) \cos(\omega_2 t) \\
 10 & = (1/2) b \omega_0 r k m_a [\cos(\omega_0 t - (-\pi/2 + \theta_00) \\
 & \quad + \omega_2 t) + \cos(\omega_0 t - (-\pi/2 + \theta_00) - \omega_2 t)] \\
 & = (1/2) b \omega_0 r k m_a \cos((\omega_0 + \omega_2)t \\
 & \quad - (-\pi/2 + \theta_00)) \\
 & \quad + (1/2) b \omega_0 r k m_a \cos((\omega_0 + \omega_2)t \\
 15 & \quad - (-\pi/2 + \theta_00)) \\
 & \quad \dots \quad (51)
 \end{aligned}$$

As is apparent from equation (51), the fifth term on the right-hand side of equation (50) forms a vector $(1/2) b \omega_0 r k m_a \exp\{j(-\pi/2 + \theta_00)\}$ on each of a complex plane based on an angular frequency $(\omega_0 + \omega_2)$ and a complex plane based on an angular frequency $(\omega_0 - \omega_2)$.

The vector as the sixth term on the right-hand side of equation (50), i.e., $m_a \cos(\omega_2 t) brkvexp\{j(\pi + \theta_00)\}$ can be rewritten to $brkv m_a \cos(\omega_0 t - (\pi + \theta_00)) \cos(\omega_2 t)$ as time expression. This time expression can further be rewritten to

$$\begin{aligned}
& \text{brkvm}_a \cos(\omega_0 t - (\pi + \theta_00)) \cos(\omega_2 t) \\
&= (1/2) \text{brkvm}_a [\cos(\omega_0 t - (\pi + \theta_00) + \omega_2 t) \\
&\quad + \cos(\omega_0 t - (\pi + \theta_00) - \omega_2 t)] \\
&= (1/2) \text{brkvm}_a \cos((\omega_0 + \omega_2)t - (\pi + \theta_00)) \\
5 &\quad + (1/2) \text{brkvm}_a \cos((\omega_0 + \omega_2)t \\
&\quad - (\pi + \theta_00)) \\
&\quad \dots (52)
\end{aligned}$$

As is apparent from equation (52), the sixth term on the right-hand side of equation (50) forms a vector $(1/2)\text{brkvm}_a \exp\{j(\pi + \theta_00)\}$ on each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

The seventh term on the right-hand side of equation (50), i.e., $m_a \cos(\omega_2 t) b \omega_0 r k \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ is the same as the fifth term on the right-hand side of equation (30). Hence, the seventh term on the right-hand side of equation (50) forms a vector $(1/2)b\omega_0 r k m_a \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ on each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

The eighth term on the right-hand side of equation (50), i.e., $m_a \cos(\omega_2 t) \text{brkv} \exp\{j(\theta_2 + \theta_00)\}$ is the same as the sixth term on the right-hand side of equation (30). Hence, the eighth term on the right-hand side of equation (50) forms a vector $(1/2)\text{brkvm}_a \exp\{j(\theta_2 + \theta_00)\}$

+ $\theta_{00}\})$ on each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

As is apparent from the above description, the 5 fifth, sixth, seventh, and eighth terms on the right-hand side of equation (50) form a complex vector Eam on each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$. The complex vector Eam 10 is given by

$$\begin{aligned} Eam = & (1/2)b\omega_0 rkm_a \exp\{j(-\pi/2 + \theta_{00})\} \\ & + (1/2)b\omega_0 rkm_a \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\} \\ & + (1/2)brkvm_a \exp\{j(\pi + \theta_{00})\} \\ & + (1/2)brkvm_a \exp\{j(\theta_2 + \theta_{00})\} \end{aligned}$$

15 ... (53)

In addition, the first to fourth terms on the right-hand side of equation (50) form a complex vector Eor given by equation (34) on a complex plane based on the angular frequency ω_0 . Four vectors that represent 20 the complex vector Eor have a geometrical relationship as shown in Fig. 5 described in the first embodiment.

Four vectors that represent the complex vector Eam, i.e., $(1/2)b\omega_0 rkm_a \exp\{j(-\pi/2 + \theta_{00})\}$, $(1/2)b\omega_0 rkm_a \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$, $(1/2)brkvm_a \exp\{j(\pi + \theta_{00})\}$, and $(1/2)brkvm_a \exp\{j(\theta_2 + \theta_{00})\}$ have a 25 geometrical relationship as shown in Fig. 7.

As shown in Fig. 7, the complex vector Eam is

the synthetic vector of four vector $(1/2)b\omega$
 $0rk_m a \exp\{j(-\pi/2 + \theta_{00})\}$, $(1/2)b\omega 0rk_m a \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\}$, $(1/2)brk_m a \exp\{j(\pi + \theta_{00})\}$, and
 $(1/2)brk_m a \exp\{j(\theta_2 + \theta_{00})\}$, which form two isosceles
5 triangles $\triangle ABC$ and $\triangle CDE$ as shown in Fig. 7. This
synthetic vector only rotates about an origin B of the
complex coordinate system as the angle θ_{00} changes.
Hence, the synthetic vector has a predetermined
magnitude independently of the change in angle θ_{00} .
10 When the bases of the isosceles triangles $\triangle ABC$ and \triangle
 CDE are synthesized, the magnitude $|E_{am}|$ of the complex
vector E_{am} is given by

$$\begin{aligned}
|E_{am}| &= 2(1/2)b\omega 0rk_m a \cos(\theta_2/2) \\
&\quad - 2(1/2)brk_m a \sin(\theta_2/2) \\
15 &= brk_m a \{\omega_0 \cos(\theta_2/2) + v \sin(\theta_2/2)\} \\
&\quad \dots (54)
\end{aligned}$$

The magnitude $|E_{or}|$ of the complex vector E_{or}
is given by equation (36). A ratio R_{am} of the magnitude
 $|E_{or}|$ of the complex vector E_{or} to the magnitude $|E_{am}|$
20 of the complex vector E_{am} , which is given by equation
(54), is given by

$$\begin{aligned}
R_{am} &= |E_{or}| / |E_{am}| \\
&= [2brk_m \{\omega_0 \sin(\theta_2/2) + v \cos(\theta_2/2)\}] \\
&\quad / [brk_m a \{\omega_0 \cos(\theta_2/2) - v \sin(\theta_2/2)\}] \\
25 &= [2\{\omega_0 \sin(\theta_2/2) + v \cos(\theta_2/2)\}] \\
&\quad / [m_a \{\omega_0 \cos(\theta_2/2) - v \sin(\theta_2/2)\}] \\
&\quad \dots (55)
\end{aligned}$$

As in the first embodiment, equation (55) that represents the ratio R_{am} has no term containing the angle θ_{00} or amplitude b . Hence, even when the angle θ_{00} changes, or the amplitude b shifts, the ratio R_{am} 5 does not change. When the flow rate is detected on the basis of the ratio R_{am} , a flow rate measurement error due to the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and 10 automatically canceled.

To obtain the flow rate of the fluid to be measured, equation (55) is rewritten to

$$v = \omega_0 \{R_{am} \cos(\theta_2/2) - 2 \sin(\theta_2/2)\} / \{R_{am} \sin(\theta_2/2) + 2 \cos(\theta_2/2)\} \quad \dots (56)$$

15 From equation (24), equation (56) can be rewritten to

$$v = \alpha \times \omega_0 \{R_{am} \cos(\theta_2/2) - 2 \sin(\theta_2/2)\} / \{R_{am} \sin(\theta_2/2) + 2 \cos(\theta_2/2)\} \quad \dots (57)$$

for $\alpha = 1/\gamma$

20 A signal conversion section 5 frequency-separates the interelectrode electromotive force E_{ac} by using a filter, as in the first embodiment, to obtain the amplitude of the component having the angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ (the 25 magnitude $|E_{am}|$ of the complex vector E_{am}). The signal conversion section 5 also obtains the amplitude of the component having the angular frequency ω_0 (the

magnitude $|E_{or}|$ of the complex vector E_{or}). The signal conversion section 5 calculates the ratio R_{am} of the magnitudes $|E_{or}|$ to $|E_{am}|$.

A flow rate output section 6 calculates a flow velocity V of the fluid to be measured by using equation 5 (57) on the basis of the ratio R_{am} obtained by the signal conversion section 5. With the above arrangement, the same effect as in the first embodiment can be obtained.

10 [Fourth Embodiment]

The fourth embodiment of the present invention will be described next. The arrangement of an electromagnetic flowmeter according to this embodiment is the same as in the first embodiment and will be described with reference to Fig. 4. A power supply section 4 according to this embodiment supplies a first sine wave exciting current having a first angular frequency ω_0 to a first exciting coil 3a. In this embodiment, $b_1 = b$, and $\theta_1 = 0$ in equation (3). Of the magnetic field generated from the first exciting coil 3a when the first exciting current is supplied from the power supply section 4, a magnetic field component B_1 which is perpendicular to both an electrode axis EAX and a measuring pipe axis PAX on the electrode axis EAX is given by equation (27).

25 The power supply section 4 also supplies a second exciting current to a second exciting coil 3b.

The second exciting current is obtained by phase-modulating a sine wave carrier having the same angular frequency ω_0 as that of the first exciting current and a predetermined phase difference θ_2 by a 5 modulated sine wave having a second angular frequency ω . With this phase modulation, the phase of the second exciting current is given by $\omega_0 t - \{\theta_2 + m_p \cos(\omega_2 t)\}$ where m_p is a phase modulation index which represents the phase deviation amount at the maximum amplitude of 10 the modulated wave.

In this embodiment, $b_2 = b$ in equation (4). Of the magnetic field generated from the second exciting coil 3b when the second exciting current is supplied from the power supply section 4, a magnetic field 15 component B_2 which is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX is given by

$$B_2 = b \cos[\omega_0 t - \{\theta_2 + m_p \cos(\omega_2 t)\}] \quad \dots (58)$$

In equation (26), $b_1 = b_2 = b$, $\theta_1 = 0$, and $\theta_{01} = \theta_0 0$. When the magnetic fields B_1 and B_2 are given 20 by equations (27) and (58), we obtain

$$\begin{aligned} E_{AC} &= E_C + E_{VC} \\ &= b \omega_0 r k \exp\{j(\pi/2 + \theta_0 0)\} \\ &\quad + b \omega_0 r k \exp\{j(-\pi/2 + m_p \cos(\omega_2 t) \\ &\quad + \theta_2 + \theta_0 0)\} \\ &\quad + b r k v \exp\{j(\theta_0 0)\} \\ &\quad + b r k v \exp\{j\{m_p \cos(\omega_2 t) + \theta_2 + \theta_0 0\}\} \end{aligned}$$

... (59)

The vector as the second term on the right-hand side of equation (59), i.e., $b\omega_0 rk \exp[j\{-\pi/2 + m_p \cos(\omega_2 t) + \theta_2 + \theta_00\}]$ can be rewritten to $b\omega_0 rk \cos\{\omega_0 t - m_p \cos(\omega_2 t) - (-\pi/2 + \theta_2 + \theta_00)\}$ as time expression. This time expression can also be rewritten to

$$\begin{aligned} & b\omega_0 rk \cos\{\omega_0 t - m_p \cos(\omega_2 t) \\ & \quad - (-\pi/2 + \theta_2 + \theta_00)\} \\ 10 & = b\omega_0 rk [\cos\{\omega_0 t \\ & \quad - (-\pi/2 + \theta_2 + \theta_00)\} \cos\{m_p \cos(\omega_2 t)\} \\ & \quad + \sin\{\omega_0 t \\ & \quad - (-\pi/2 + \theta_2 + \theta_00)\} \sin\{m_p \cos(\omega_2 t)\}] \end{aligned} \quad \dots (60)$$

15 In equation (60), $\cos\{m_p \cos(\omega_2 t)\}$ and $\sin\{m_p \cos(\omega_2 t)\}$ can be rewritten to

$$\cos\{m_p \cos(\omega_2 t)\} = J_0(m_p) + 2 \sum_{n=2,4,\dots}^{\infty} (-1)^{n/2} J_n(m_p) \cos(n\omega_2 t) \quad \dots (61)$$

$$\sin\{m_p \cos(\omega_2 t)\} = 2 \sum_{n=1,3,\dots}^{\infty} (-1)^{(n-1)/2} J_n(m_p) \cos(n\omega_2 t) \quad \dots (62)$$

20 In equations (61) and (62), $J_n(m_p)$ ($n = 0, 1, 2, \dots$) is known as a Bessel function of fractional order. The Bessel function of fractional order, $J_n(m_p)$

is given by

$$J_n(m_p) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!(n+k)!} \left(\frac{m_p}{2}\right)^{n+2k} \quad \dots (63)$$

25 In equation (63), $k!$ indicates the factorial of k . When only a case wherein $n = 0$ or 1 is applied to

equations (61) and (62), equation (60) can be rewritten to

$$\begin{aligned}
 & b\omega_0 r k \cos(\omega_0 t - m_p \cos(\omega_2 t) \\
 & \quad - (-\pi/2 + \theta_2 + \theta_00)) \\
 5 & = b\omega_0 r k [\cos(\omega_0 t - (-\pi/2 + \theta_2 + \theta_00)) J_0(m_p) \\
 & \quad + \sin(\omega_0 t \\
 & \quad - (-\pi/2 + \theta_2 + \theta_00)) 2 J_1(m_p) \cos(\omega_2 t)] \\
 & = b\omega_0 r k [J_0(m_p) \cos(\omega_0 t - (-\pi/2 + \theta_2 + \theta_00)) \\
 & \quad + J_1(m_p) \sin((\omega_0 + \omega_2)t - (-\pi/2 + \theta_2 \\
 10 & \quad + \theta_00))] \\
 & \quad + J_1(m_p) \sin((\omega_0 - \omega_2)t - (-\pi/2 + \theta_2 \\
 & \quad + \theta_00))] \\
 & = b\omega_0 r k J_0(m_p) \cos(\omega_0 t - (-\pi/2 + \theta_2 + \theta_00)) \\
 & \quad + b\omega_0 r k J_1(m_p) \cos((\omega_0 + \omega_2)t - (\theta_2 + \theta_00)) \\
 15 & \quad + b\omega_0 r k J_1(m_p) \cos((\omega_0 - \omega_2)t - (\theta_2 + \theta_00)) \\
 & \quad \dots \quad (64)
 \end{aligned}$$

As is apparent from equation (64), the second term on the right-hand side of equation (59) forms a vector $b\omega_0 r k J_0(m_p) \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ on a complex plane based on the angular frequency ω_0 . The second term also forms a vector $b\omega_0 r k J_1(m_p) \exp\{j(\theta_2 + \theta_00)\}$ on each of a complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and a complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

25 The vector as the fourth term on the right-hand side of equation (59), i.e., $\text{brkvexp}[j\{m_p \cos(\omega_2 t) + \theta_2 + \theta_00\}]$ can be rewritten to

brkv $\cos\{\omega_0 t - m_p \cos(\omega_2 t) - (\theta_2 + \theta_00)\}$ as time expression. This time expression can also be rewritten to

$$\begin{aligned}
 & \text{brkv}\cos\{\omega_0 t - m_p \cos(\omega_2 t) - (\theta_2 + \theta_00)\} \\
 5 & = \text{brkv}[\cos\{\omega_0 t \\
 & \quad - (\theta_2 + \theta_00)\}\cos\{m_p \cos(\omega_2 t)\} \\
 & \quad + \sin\{\omega_0 t - (\theta_2 + \theta_00)\}\sin\{m_p \cos(\omega_2 t)\}] \\
 & \quad \dots (65)
 \end{aligned}$$

Like the second term on the right-hand side of equation (59), when the Bessel function of fractional order $J_n(m_p)$ is applied, equation (65) can be rewritten to

$$\begin{aligned}
 & \text{brkv}\cos\{\omega_0 t - m_p \cos(\omega_2 t) - (\theta_2 + \theta_00)\} \\
 & = \text{brkv}[\cos\{\omega_0 t - (\theta_2 + \theta_00)\}J_0 m_p \\
 15 & \quad + \sin\{\omega_0 t - (\theta_2 + \theta_00)\}2J_1(m_p)\cos(\omega_2 t)] \\
 & = \text{brkv}[J_0(m_p)\cos\{\omega_0 t - (\theta_2 + \theta_00)\} \\
 & \quad + J_1(m_p)\cos\{(\omega_0 + \omega_2)t - (\pi/2 + \theta_2 + \theta_00)\} \\
 & \quad + J_1(m_p)\cos\{(\omega_0 - \omega_2)t - (\pi/2 + \theta_2 + \theta_00)\}] \\
 & \quad \dots (66)
 \end{aligned}$$

20 As is apparent from equation (66), the fourth term on the right-hand side of equation (59) forms a vector $\text{brkv}J_0(m_p)\exp\{j(\theta_2 + \theta_00)\}$ on the complex plane based on the angular frequency ω_0 . The fourth term also forms a vector $\text{brkv}J_1(m_p)\exp\{j(\pi/2 + \theta_2 + \theta_00)\}$ on 25 each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

As is apparent from the above description, the second and fourth terms on the right-hand side of equation (59) form a complex vector E_{pm} on each of the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$. The complex vector E_{pm} is given by

$$E_{pm} = b\omega_0 r k J_1(m_p) \exp\{j(\theta_2 + \theta_{00})\} + b r k v J_1(m_p) \exp\{j(\pi/2 + \theta_2 + \theta_{00})\} \dots (67)$$

10 In addition, the first to fourth terms on the right-hand side of equation (59) form a complex vector E_{or} on the complex plane based on the angular frequency ω_0 . The complex vector E_{or} is given by

$$E_{or} = b\omega_0 r k \exp\{j(\pi/2 + \theta_{00})\} + b r k v \exp\{j(\theta_{00})\} + b\omega_0 r k J_0(m_p) \exp\{j(-\pi/2 + \theta_2 + \theta_{00})\} + b r k v J_0(m_p) \exp\{j(\theta_2 + \theta_{00})\} \dots (68)$$

The magnitude $|E_{pm}|$ of the complex vector E_{pm} given by equation (67) is given by

$$20 |E_{pm}| = b r k \{J_1(m_p)^2 \{(\omega_0^2 + v^2)\}\}^{1/2} \dots (69)$$

The magnitude $|E_{or}|$ of the complex vector E_{or} given by equation (68) is given by

$$25 |E_{or}| = b r k \{[v + J_0(m_p) \sin(\theta_2) \omega_0 + J_0(m_p) \cos(\theta_2) v]^2 + \{(\omega_0 - J_0(m_p) \cos(\theta_2) \omega_0 + J_0(m_p) \sin(\theta_2) v)^2\}^{1/2}\}^{1/2} \dots (70)$$

A ratio R_{pm} of the magnitude $|E_{or}|$ of the complex vector E_{or} to the magnitude $|E_{pm}|$ of the complex vector E_{pm} is given by

$$R_{pm} = |E_{or}| / |E_{pm}| \quad \dots(71)$$

5 The magnitude $|E_{pm}|$ given by equation (69) and the magnitude $|E_{or}|$ given by equation (70) have no term containing the angle θ_{00} . The magnitudes $|E_{or}|$ and $|E_{pm}|$ contain brk . However, when the ratio R_{pm} is obtained by equation (71), brk is erased from the ratio

10 R_{pm} .

Hence, even when the angle θ_{00} changes, or the amplitude (the amplitude of the carrier component of the magnetic field B_2) b of the magnetic field B_1 shifts, the ratio R_{pm} does not change. When the flow rate is detected on the basis of the ratio R_{pm} , a flow rate measurement error due to the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

15 20 When equations (69) and (70) are substituted into equation (71), and equation (71) is solved about v , we obtain

$$v = [\omega_0 \{-2J_0(m_p) \sin(\theta_2) + \{2J_0(m_p)^2 - J_0(m_p)^4 + 2J_0(m_p)^2 J_1(m_p)^2 R_{pm}^2 - 1 + 2J_1(m_p)^2 R_{pm}^2 - J_1(m_p)^4 R_{pm}^4\}^{1/2}\}] / \{J_0(m_p)^2 + 1 + 2J_0(m_p) \cos(\theta_2) - J_1(m_p)^2 R_{pm}^2\} \quad \dots(72)$$

From equation (24), equation (72) can be
rewritten to

$$\begin{aligned} v = \alpha \times & [\omega_0 \{-2J_0(m_p) \sin(\theta/2) \\ & + \{2J_0(m_p)^2 - J_0(m_p)^4 + 2J_0(m_p)^2 J_1(m_p)^2 Rpm^2 - 1 \\ & + 2J_1(m_p)^2 Rpm^2 - J_1(m_p)^4 Rpm^4\}^{1/2}\}] \\ & /\{J_0(m_p)^2 + 1 + 2J_0(m_p) \cos(\theta/2) - J_1(m_p)^2 Rpm^2\} \end{aligned} \quad \dots (73)$$

for $\alpha = 1/\gamma$

A signal conversion section 5
frequency-separates an interelectrode electromotive
force Eac by using a filter, as in the first embodiment,
10 to obtain the amplitude of the component having the
angular frequency $(\omega_0 + \omega/2)$ or $(\omega_0 - \omega/2)$ (the
magnitude $|Epm|$ of the complex vector Epm). The signal
conversion section 5 also obtains the amplitude of the
15 component having the angular frequency ω_0 (the
magnitude $|Eor|$ of the complex vector Eor). The signal
conversion section 5 calculates the ratio Rpm of the
magnitudes $|Eor|$ to $|Epm|$.

A flow rate output section 6 calculates a flow
20 velocity V of the fluid to be measured by using equation
(73) on the basis of the ratio Rpm obtained by the
signal conversion section 5. With the above
arrangement, the same effect as in the first embodiment
can be obtained.

25 [Fifth Embodiment]

The fifth embodiment of the present invention
will be described next. The arrangement of an

electromagnetic flowmeter according to this embodiment is the same as in the first embodiment and will be described with reference to Fig. 4. A power supply section 4 according to this embodiment supplies a first 5 exciting current to a first exciting coil 3a. The first exciting current is obtained by phase-modulating a sine wave carrier having a first angular frequency ω_0 by a modulated sine wave having a second angular frequency ω 2. In this embodiment, $b_1 = b$, and $\theta_1 = 0$ in equation 10 (3).

With this phase modulation, the phase of the first exciting current is given by $\omega_0 t - m_p \cos(\omega_2 t) + \pi$.

Of the magnetic field generated from the first 15 exciting coil 3a when the first exciting current is supplied from the power supply section 4, a magnetic field component B_1 which is perpendicular to both an electrode axis EAX and a measuring pipe axis PAX on the electrode axis EAX is given by

20
$$B_1 = b \cos\{\omega_0 t - m_p \cos(\omega_2 t) + \pi\} \quad \dots (74)$$

The power supply section 4 also supplies a second exciting current to a second exciting coil 3b. The second exciting current is obtained by phase-modulating a sine wave carrier having the same 25 angular frequency ω_0 as that of the first exciting current and a predetermined phase difference θ_2 by a modulated sine wave having the same angular frequency ω

2 as that of the modulated wave component of the first exciting current and an opposite phase.

With this phase modulation, the phase of the second exciting current is given by $\omega_0 t - \{\theta_2 + 5 m_p \cos(\omega_2 t)\}$.

In this embodiment, $b_2 = b$ in equation (4). Of the magnetic field generated from the second exciting coil 3b when the second exciting current is supplied from the power supply section 4, a magnetic field 10 component B_2 which is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX is given by equation (58).

The magnitude $|E_{pm}|$ of a complex vector E_{pm} , which is obtained in accordance with the same procedures 15 as in the fourth embodiment, is given by

$$|E_{pm}| = 2^{1/2} brk [J_1(m_p)^2 \{v^2 + \omega_0^2 + \omega_0^2 \cos(\theta_2) - v^2 \cos(\theta_2) - 2v\omega_0 \sin(\theta_2)\}]^{1/2} \dots (75)$$

The magnitude $|E_{or}|$ of a complex vector E_{or} is 20 given by

$$|E_{or}| = 2^{1/2} brk [J_0(m_p)^2 \{v^2 + \omega_0^2 - \omega_0^2 \cos(\theta_2) - v^2 \cos(\theta_2) + 2v\omega_0 \sin(\theta_2)\}]^{1/2} \dots (76)$$

The magnitude $|E_{pm}|$ given by equation (75) and 25 the magnitude $|E_{or}|$ given by equation (76) have no term containing an angle θ_{00} .

The magnitudes $|E_{or}|$ and $|E_{pm}|$ contain brk.

However, when a ratio Rpm is obtained by equation (71), brk is erased from the ratio Rpm. Hence, when the flow rate is detected on the basis of the ratio Rpm, a flow rate measurement error due to the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

When equations (75) and (76) are substituted into equation (71), and equation (71) is solved about v , we obtain

10 we obtain

$$\begin{aligned}
 v = & \omega_0 \left[-\{J_0(m_p)^2 \cos(\theta_2) \sin(\theta_2) \right. \\
 & + J_1(m_p)^2 \sin(\theta_2) \cos(\theta_2) Rpm^2 \\
 & + J_1(m_p)^2 \sin(\theta_2) Rpm^2 + J_0(m_p)^2 \sin(\theta_2) \} \\
 & + 2 |J_0(m_p) J_1(m_p) \{ \cos(\theta_2) + 1 \} Rpm | \} \\
 & / \{ 2 J_0(m_p)^2 \cos(\theta_2) + J_0(m_p)^2 \\
 & + J_0(m_p)^2 \cos(\theta_2)^2 - J_1(m_p)^2 Rpm^2 \\
 & + J_1(m_p)^2 \cos(\theta_2)^2 Rpm^2 \} \\
 15 & \dots (77)
 \end{aligned}$$

20 rewritten to

$$\begin{aligned}
 v = & \alpha \times \omega_0 \left[-\{J_0(m_p)^2 \cos(\theta_2) \sin(\theta_2) \right. \\
 & + J_1(m_p)^2 \sin(\theta_2) \cos(\theta_2) Rpm^2 \\
 & + J_1(m_p)^2 \sin(\theta_2) Rpm^2 + J_0(m_p)^2 \sin(\theta_2) \} \\
 & + 2 |J_0(m_p) J_1(m_p) \{ \cos(\theta_2) + 1 \} Rpm | \} \\
 & / \{ 2 J_0(m_p)^2 \cos(\theta_2) + J_0(m_p)^2 \\
 & + J_0(m_p)^2 \cos(\theta_2)^2 - J_1(m_p)^2 Rpm^2 \\
 & + J_1(m_p)^2 \cos(\theta_2)^2 Rpm^2 \} \\
 25 & \dots
 \end{aligned}$$

for $\alpha = 1/\gamma$

... (78)

A signal conversion section 5 frequency-separates an interelectrode electromotive force Eac by using a filter, as in the first embodiment, 5 to obtain the amplitude of the component having the angular frequency $(\omega_0 + \omega_2)$ or $(\omega_0 - \omega_2)$ (the magnitude $|Epm|$ of the complex vector Epm).

The signal conversion section 5 also obtains the amplitude of the component having the angular 10 frequency ω_0 (the magnitude $|Eor|$ of the complex vector Eor). The signal conversion section 5 calculates the ratio Rpm of the magnitudes $|Eor|$ to $|Epm|$.

A flow rate output section 6 calculates a flow velocity V of the fluid to be measured by using equation 15 (78) on the basis of the ratio Rpm obtained by the signal conversion section 5. With the above arrangement, the same effect as in the first embodiment can be obtained.

[Sixth Embodiment]

20 The sixth embodiment of the present invention will be described next. The arrangement of an electromagnetic flowmeter according to this embodiment is the same as in the first embodiment and will be described with reference to Fig. 4. A power supply 25 section 4 according to this embodiment supplies a first sine wave exciting current having a first angular frequency ω_0 to a first exciting coil 3a.

In this embodiment, $b_1 = b$, and $\theta_1 = 0$ in equation (3). Of the magnetic field generated from the first exciting coil 3a when the first exciting current is supplied from the power supply section 4, a magnetic field component B_1 which is perpendicular to both an electrode axis EAX and a measuring pipe axis PAX on the electrode axis EAX is given by equation (27).

The power supply section 4 also supplies a second exciting current to a second exciting coil 3b.

10 The second exciting current is obtained by frequency-modulating a sine wave carrier having the same angular frequency ω_0 as that of the first exciting current and a predetermined phase difference θ_2 by a modulated sine wave having a second angular frequency ω

15 2.

With this phase modulation, the phase of the second exciting current is given by $\omega_0 t - \{\theta_2 + m_f \sin(\omega_2 t)\}$ where m_f is a frequency modulation index which represents the frequency deviation amount at the

20 maximum amplitude of the modulated wave.

In this embodiment, $b_2 = b$ in equation (4). Of the magnetic field generated from the second exciting coil 3b when the second exciting current is supplied from the power supply section 4, a magnetic field component B_2 which is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX is given by

$$B_2 = b \cos[\omega_0 t - \{\theta_2 + m_f \sin(\omega_2 t)\}] \quad \dots (79)$$

In equation (26), $b_1 = b_2 = b$, $\theta_1 = 0$, and $\theta_0 = \theta_00$. When the magnetic fields B_1 and B_2 are given by equations (27) and (79), we obtain

$$\begin{aligned} 5 \quad E_{ac} &= E_C + E_{vc} \\ &= b \omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\ &\quad + b \omega_0 r k \exp\{j(-\pi/2 + m_f \sin(\omega_2 t) \\ &\quad + \theta_2 + \theta_00)\} \\ &\quad + b r k v \exp\{j(\theta_00)\} \\ &\quad + b r k v \exp\{j\{m_f \sin(\omega_2 t) + \theta_2 + \theta_00\}\} \\ 10 \quad &\quad \dots (80) \end{aligned}$$

The vector as the second term on the right-hand side of equation (80), i.e., $b \omega_0 r k \exp\{j\{-\pi/2 + m_f \sin(\omega_2 t) + \theta_2 + \theta_00\}\}$ can be rewritten to $b \omega_0 r k \cos\{\omega_0 t - m_f \sin(\omega_2 t) - (-\pi/2 + \theta_2 + \theta_00)\}$ as time expression. This time expression can also be rewritten to

$$\begin{aligned} 20 \quad &b \omega_0 r k \cos\{\omega_0 t - m_f \sin(\omega_2 t) \\ &\quad - (-\pi/2 + \theta_2 + \theta_00)\} \\ &= b \omega_0 r k [\cos\{\omega_0 t \\ &\quad - (-\pi/2 + \theta_2 + \theta_00)\} \cos\{m_f \sin(\omega_2 t)\} \\ &\quad + \sin\{\omega_0 t \\ &\quad - (-\pi/2 + \theta_2 + \theta_00)\} \sin\{m_f \sin(\omega_2 t)\}] \\ &\quad \dots (81) \end{aligned}$$

25 In equation (81), $\cos\{m_f \sin(\omega_2 t)\}$ and $\sin\{m_f \sin(\omega_2 t)\}$ can be rewritten to

$$\cos\{m_f \sin(\omega_0 t)\} = J_0(m_f) + 2 \sum_{n=2,4,\dots}^{\infty} (-1)^{n/2} J_n(m_f) \sin(n\omega_0 t) \quad \dots (82)$$

$$\sin\{m_f \sin(\omega_0 t)\} = 2 \sum_{n=1,3,\dots}^{\infty} (-1)^{(n-1)/2} J_n(m_f) \sin(n\omega_0 t) \quad \dots (83)$$

5 In equations (82) and (83), the Bessel function of fractional order, $J_n(m_f)$ ($n = 0, 1, 2, \dots$) is given by

$$J_n(m_f) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!(n+k)!} \left(\frac{m_f}{2}\right)^{n+2k} \quad \dots (84)$$

10 When only a case wherein $n = 0$ or 1 is applied to equations (82) and (83), equation (81) can be rewritten to

$$\begin{aligned} & b\omega_0 r k \cos\{\omega_0 t - m_f \sin(\omega_0 t) \\ & \quad - (-\pi/2 + \theta_2 + \theta_00)\} \\ & = b\omega_0 r k [\cos\{\omega_0 t - (-\pi/2 + \theta_2 + \theta_00)\} J_0(m_f) \\ & \quad + \sin\{\omega_0 t \\ & \quad - (-\pi/2 + \theta_2 + \theta_00)\} 2 J_1(m_f) \sin(\omega_0 t)] \\ & = b\omega_0 r k [J_0(m_f) \cos\{\omega_0 t - (-\pi/2 + \theta_2 + \theta_00)\} \\ & \quad - J_1(m_f) \cos\{(\omega_0 + \omega_2)t - (-\pi/2 + \theta_2 \\ & \quad + \theta_00)\} \\ & \quad + J_1(m_f) \cos\{(\omega_0 - \omega_2)t - (-\pi/2 + \theta_2 \\ & \quad + \theta_00)\}] \end{aligned} \quad \dots (85)$$

15 As is apparent from equation (85), the second term on the right-hand side of equation (80) forms a vector $b\omega_0 r k J_0(m_f) \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ on a complex plane based on the angular frequency ω_0 , a vector $b\omega_0 r k \{-J_1(m_f)\} \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ on a complex plane

based on the angular frequency ($\omega_0 + \omega_2$), and a vector $b\omega_0 r k_j(m_f) \exp\{j(-\pi/2 + \theta_2 + \theta_00)\}$ on a complex plane based on the angular frequency ($\omega_0 - \omega_2$).

The vector as the fourth term on the
 5 right-hand side of equation (80), i.e.,
 $\text{brkvexp}[j\{m_f \sin(\omega_2 t) + \theta_2 + \theta_00\}]$ can be rewritten to
 $\text{brkv}\cos\{\omega_0 t - m_f \sin(\omega_2 t) - (\theta_2 + \theta_00)\}$ as time
 expression. This time expression can also be rewritten
 to

$$\begin{aligned}
 10 \quad & \text{brkv}\cos\{\omega_0 t - m_f \sin(\omega_2 t) - (\theta_2 + \theta_00)\} \\
 & = \text{brkv}[\cos\{\omega_0 t \\
 & \quad - (\theta_2 + \theta_00)\} \cos\{m_f \sin(\omega_2 t)\} \\
 & \quad + \sin\{\omega_0 t - (\theta_2 + \theta_00)\} \sin\{m_f \sin(\omega_2 t)\}] \\
 & \quad \dots (86)
 \end{aligned}$$

15 Like the second term on the right-hand side of equation (80), when the Bessel function of fractional order $J_n(m_f)$ is applied, equation (86) can be rewritten to

$$\begin{aligned}
 20 \quad & \text{brkv}\cos\{\omega_0 t - m_f \sin(\omega_2 t) - (\theta_2 + \theta_00)\} \\
 & = \text{brkv}[\cos\{\omega_0 t - (\theta_2 + \theta_00)\} J_0 m_f \\
 & \quad + \sin\{\omega_0 t - (\theta_2 + \theta_00)\} 2 J_1(m_f) \sin(\omega_2 t)] \\
 & = \text{brkv}[J_0(m_f) \cos\{\omega_0 t - (\theta_2 + \theta_00)\} \\
 & \quad - J_1(m_f) \cos\{(\omega_0 + \omega_2)t - (\theta_2 + \theta_00)\} \\
 & \quad + J_1(m_f) \cos\{(\omega_0 - \omega_2)t - (\theta_2 + \theta_00)\}] \\
 & \quad \dots (87)
 \end{aligned}$$

As is apparent from equation (87), the fourth term on the right-hand side of equation (80) forms a

vector $\text{brkvJ}_0(m_f) \exp\{j(\theta_2 + \theta_00)\}$ on the complex plane based on the angular frequency ω_0 , a vector $\text{brkv}\{-j_1(m_f)\} \exp\{j(\theta_2 + \theta_00)\}$ on the complex plane based on the angular frequency $(\omega_0 + \omega_2)$, and a vector 5 $\text{brkvJ}_1(m_f) \exp\{j(\theta_2 + \theta_00)\}$ on the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

As is apparent from the above description, the second and fourth terms on the right-hand side of equation (80) form complex vectors having the same 10 magnitude and reverse directions on the complex plane based on the angular frequency $(\omega_0 + \omega_2)$ and the complex plane based on the angular frequency $(\omega_0 - \omega_2)$.

A complex vector E_{fm} formed on the complex 15 plane based on the angular frequency $(\omega_0 - \omega_2)$ is given by

$$\begin{aligned} E_{fm} = & b\omega_0 r k J_1(m_f) \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\ & + \text{brkvJ}_1(m_f) \exp\{j(\theta_2 + \theta_00)\} \end{aligned} \quad \dots (88)$$

20 In addition, the first to fourth terms on the right-hand side of equation (80) form a complex vector E_{or} on the complex plane based on the angular frequency ω_0 . The complex vector E_{or} is given by

$$\begin{aligned} E_{or} = & b\omega_0 r k \exp\{j(\pi/2 + \theta_00)\} \\ & + \text{brkv} \exp\{j(\theta_00)\} \\ & + b\omega_0 r k J_0(m_f) \exp\{j(-\pi/2 + \theta_2 + \theta_00)\} \\ & + \text{brkvJ}_0(m_f) \exp\{j(\theta_2 + \theta_00)\} \end{aligned} \quad \dots (89)$$

A ratio R_{fm} of the magnitude $|E_{or}|$ of the complex vector E_{or} to the magnitude $|E_{fm}|$ of the complex vector E_{fm} is given by

$$R_{fm} = |E_{or}| / |E_{fm}| \quad \dots (90)$$

5 When the magnitude $|E_{or}|$ of the complex vector E_{or} obtained from equation (89) and the magnitude $|E_{fm}|$ of the complex vector E_{fm} obtained from equation (88) are substituted into equation (90), and equation (90) is solved about v , we obtain

10

$$v = [\omega_0 \{-2J_0(m_f) \sin(\theta_2) + \{2J_0(m_f)^2 - J_0(m_f)^4 + 2J_0(m_f)^2 J_1(m_f)^2 R_{fm}^2 - 1 + 2J_1(m_f)^2 R_{fm}^2 - J_1(m_f)^4 R_{fm}^4\}^{1/2}\} / \{J_0(m_f)^2 + 1 + 2J_0(m_f) \cos(\theta_2) - J_1(m_f)^2 R_{fm}^2\}] \quad \dots (91)$$

15 Equation (91) has no term containing an angle θ_{00} or the amplitude (the amplitude of the carrier component of the magnetic field B_2) b of the magnetic field B_1 . Hence, when the flow rate is detected on the basis of the ratio R_{fm} , a flow rate measurement error 20 due to the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

From equation (24), equation (91) can be 25 rewritten to

$$v = \alpha \times [\omega_0 \{-2J_0(m_f) \sin(\theta_2) + \{2J_0(m_f)^2 - J_0(m_f)^4 + 2J_0(m_f)^2 J_1(m_f)^2 R_{fm}^2 - 1\}$$

$$\begin{aligned}
 & + 2J_1(m_f)^2 Rfm^2 - J_1(m_f)^4 Rfm^4 \}^{1/2} \} \\
 & / \{ J_0(m_f)^2 + 1 + 2J_0(m_f) \cos(\theta_2) - J_1(m_f)^2 Rfm^2 \} \\
 \text{for } \alpha & = 1/\gamma \quad \dots (92)
 \end{aligned}$$

A signal conversion section 5

5 frequency-separates an interelectrode electromotive force Eac by using a filter, as in the first embodiment, to obtain the amplitude of the component having the angular frequency ($\omega_0 - \omega_2$) (the magnitude $|Efm|$ of the complex vector Efm). The signal conversion section 10 5 also obtains the amplitude of the component having the angular frequency ω_0 (the magnitude $|Eor|$ of the complex vector Eor). The signal conversion section 5 calculates the ratio Rfm of the magnitudes $|Eor|$ to $|Efm|$.

15 A flow rate output section 6 calculates a flow velocity V of the fluid to be measured by using equation (92) on the basis of the ratio Rfm obtained by the signal conversion section 5. With the above arrangement, the same effect as in the first embodiment 20 can be obtained.

[Seventh Embodiment]

The seventh embodiment of the present invention will be described next. The arrangement of an electromagnetic flowmeter according to this embodiment 25 is the same as in the first embodiment and will be described with reference to Fig. 4.

A power supply section 4 according to this

embodiment supplies a first exciting current to a first exciting coil 3a. The first exciting current is obtained by frequency-modulating a sine wave carrier having a first angular frequency ω_0 by a modulated sine 5 wave having a second angular frequency ω_2 . In this embodiment, $b_1 = b$, and $\theta_1 = 0$ in equation (3).

With this frequency modulation, the phase of the first exciting current is given by $\omega_0 t - m_f \sin(\omega_2 t + \pi)$.

10 Of the magnetic field generated from the first exciting coil 3a when the first exciting current is supplied from the power supply section 4, a magnetic field component B_1 which is perpendicular to both an electrode axis EAX and a measuring pipe axis PAX on the 15 electrode axis EAX is given by

$$B_1 = b \cos\{\omega_0 t - m_f \sin(\omega_2 t + \pi)\} \quad \dots(93)$$

The power supply section 4 also supplies a second exciting current to a second exciting coil 3b.

20 The second exciting current is obtained by frequency-modulating a sine wave carrier having the same angular frequency ω_0 as that of the first exciting current and a predetermined phase difference θ_2 by a modulated sine wave having the same angular frequency ω_2 as that of the modulated wave component of the first 25 exciting current and an opposite phase.

With this frequency modulation, the phase of the second exciting current is given by $\omega_0 t - \theta_2 +$

$m_f \sin(\omega_2 t)$.

In this embodiment, $b_2 = b$ in equation (4). Of the magnetic field generated from the second exciting coil 3b when the second exciting current is supplied 5 from the power supply section 4, a magnetic field component B_2 which is perpendicular to both the electrode axis EAX and the measuring pipe axis PAX on the electrode axis EAX is given by equation (79).

The magnitude $|E_{or}|$ of a complex vector E_{or} 10 and the magnitude $|E_{fm}|$ of a complex vector E_{fm} are obtained in accordance with the same procedures as in the sixth embodiment. When the magnitudes $|E_{or}|$ and $|E_{fm}|$ are substituted into equation (90), and equation (90) is solved about v , we obtain

$$\begin{aligned} 15 \quad v = & \omega_0 [-\{J_0(m_f)^2 \cos(\theta_2) \sin(\theta_2) \\ & + J_1(m_f)^2 \sin(\theta_2) \cos(\theta_2) R_{fm}^2 \\ & + J_1(m_f)^2 \sin(\theta_2) R_{fm}^2 + J_0(m_f)^2 \sin(\theta_2) \} \\ & + 2 |J_0(m_f) J_1(m_f) \{ \cos(\theta_2) + 1 \} R_{fm}|] \\ & / \{ 2 J_0(m_f)^2 \cos(\theta_2) + J_0(m_f)^2 \\ 20 \quad & + J_0(m_f)^2 \cos(\theta_2)^2 - J_1(m_f)^2 R_{fm}^2 \\ & + J_1(m_f)^2 \cos(\theta_2)^2 R_{fm}^2 \} \end{aligned}$$

... (94)

Equation (94) has no term containing an angle θ_{00} or an amplitude b of the carrier components of the 25 magnetic fields B_1 and B_2 . Hence, when the flow rate is detected on the basis of a ratio R_{fm} , a flow rate measurement error due to the variation in delay of the

magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field can be quickly and automatically canceled.

From equation (24), equation (94) can be 5 rewritten to

$$\begin{aligned} V = \alpha \times \omega_0 & \left[-\{J_0(m_f)^2 \cos(\theta_2) \sin(\theta_2) \right. \\ & + J_1(m_f)^2 \sin(\theta_2) \cos(\theta_2) Rfm^2 \\ & + J_1(m_f)^2 \sin(\theta_2) Rfm^2 + J_0(m_f)^2 \sin(\theta_2) \} \\ & + 2 |J_0(m_f) J_1(m_f) \{ \cos(\theta_2) + 1 \} Rfm | \} \\ 10 & / \{ 2 J_0(m_f)^2 \cos(\theta_2) + J_0(m_f)^2 \\ & + J_0(m_f)^2 \cos(\theta_2)^2 - J_1(m_f)^2 Rfm^2 \\ & + J_1(m_f)^2 \cos(\theta_2)^2 Rfm^2 \} \\ \text{for } \alpha = 1/\gamma & \dots (95) \end{aligned}$$

A signal conversion section 5 15 frequency-separates an interelectrode electromotive force Eac by using a filter, as in the first embodiment, to obtain the amplitude of the component having the angular frequency $(\omega_0 - \omega_2)$ (the magnitude $|Efm|$ of the complex vector Efm). The signal conversion section 20 5 also obtains the amplitude of the component having the angular frequency ω_0 (the magnitude $|Eor|$ of the complex vector Eor). The signal conversion section 5 calculates the ratio Rfm of the magnitudes $|Eor|$ to $|Efm|$.

A flow rate output section 6 calculates a flow 25 velocity V of the fluid to be measured by using equation (95) on the basis of the ratio Rfm obtained by the

signal conversion section 5. With the above arrangement, the same effect as in the first embodiment can be obtained.

In the fourth to seventh embodiments, only a 5 case wherein $n = 0$ or 1 is applied in expanding the Bessel function of fractional order. Instead, the amplitude ratio R_{pm} or R_{fm} is obtained by separating a component having a sum frequency $(\omega_0 + \xi\omega_2)$ or a difference frequency $(\omega_0 - \xi\omega_2)$ of the first angular 10 frequency ω_0 and a third angular frequency (an angular frequency ξ -times higher than the second angular frequency ω_2) $\xi\omega_2$ from the interelectrode electromotive force E_{ac} . The flow velocity V of the fluid to be measured is calculated from the amplitude 15 ratio R_{pm} or R_{fm} . In this case, even when ξ is an integer of 2 or more, the flow velocity V can be calculated, as in the fourth to seventh embodiments, by applying a case wherein $n = 2$ or more in expanding the Bessel function of fractional order.

20 In the first to seventh embodiments, in-phase component noise can be removed. Hence, the rectangular wave exciting method need not be used. Since the sine wave exciting method which uses a sine wave for an exciting current can be used, high-frequency excitation 25 can be executed. When high-frequency excitation is used, $1/f$ noise can be removed, and the response to a change in flow rate can be increased.

The magnetic fields B_1 and B_2 applied to the fluid to be measured only need to satisfy the conditions described in each embodiment. Hence, the exciting coils may be arranged symmetrically by setting them such that

5 the offset distance d_1 from the plane PLN to the axis of the first exciting coil 3a is equal to the offset distance d_2 for the plane PLN to the axis of the second exciting coil 3b. Alternatively, the exciting coils may be arranged asymmetrically by setting different offset

10 distances d_1 and d_2 .

The angle made by the electrode axis EAX and the axis of the first exciting coil 3a may be equal to the angle made by the electrode axis EAX and the axis of the second exciting coil 3b (e.g., 90°). Alternatively,

15 as shown in Fig. 8, the angle made by the electrode axis EAX and the axis of the first exciting coil 3a may be different from the angle made by the electrode axis EAX and the axis of the second exciting coil 3b. In the first to seventh embodiments, the phase difference θ_2

20 may be 0.

As the electrodes 2a and 2b used in the first to seventh embodiments, electrodes which are exposed from the inner wall of the measuring pipe 1 and come into contact with the fluid to be measured may be used,

25 as shown in Fig. 9. Alternatively, as shown in Fig. 10, capacitively coupled electrodes which do not come into contact with the fluid to be measured may be used. When

capacitively coupled electrodes are used, the electrodes 2a and 2b are covered with a lining 10 made of ceramic or Teflon (registered trademark) and formed on the inner wall of the measuring pipe 1.

5 In the first to seventh embodiments, the two electrodes 2a and 2b are used. However, the present invention is not limited to this. The present invention can also be applied to an electromagnetic flowmeter having only one electrode. When only one electrode is
10 used, a ground ring is provided in the measuring pipe 1 to set the potential of the fluid to be measured to the ground potential. An electromotive force (the potential difference from the ground potential) generated in the single electrode is detected by the signal conversion
15 section 5. When the two electrodes 2a and 2b are used, the electrode axis EAX forms a straight line that connects the electrodes 2a and 2b. When only one electrode is used, it is assumed that a virtual electrode is arranged on the plane PLN including the
20 single real electrode at a position opposite to the real electrode with respect to the measuring pipe axis PAX. The straight line that connects the real electrode and the virtual electrode at this time corresponds to the electrode axis EAX.

25 The means for calculating the ratio R_{am} in the signal conversion section 5 and the flow rate output section 6 in the first embodiment, the means for

obtaining the phase differences ϕ_{or} and ϕ_{am} in the signal conversion section 5 and the flow rate output section 6 in the second embodiment, the means for calculating the ratio R_{am} in the signal conversion section 5 and the flow rate output section 6 in the third embodiment, the means for calculating the ratio R_{pm} in the signal conversion section 5 and the flow rate output section 6 in the fourth and fifth embodiments, and the means for calculating the ratio R_{fm} in the signal conversion section 5 and the flow rate output section 6 in the sixth and seventh embodiments can be implemented by, e.g., a computer.

According to the present invention, a first magnetic field having a first frequency is applied to a fluid while a second magnetic field obtained by amplitude-, phase-, or frequency-modulating a carrier having the first frequency by a modulated wave having a second frequency is simultaneously applied to the fluid. Alternatively, a first magnetic field obtained by amplitude-, phase-, or frequency-modulating a carrier having a first frequency by a modulated wave having a second frequency is applied to a fluid while a second magnetic field obtained by amplitude-, phase-, or frequency-modulating a carrier having the first frequency by a modulated wave having the same frequency as that of the modulated wave of the first magnetic field and an opposite phase is simultaneously applied to

the fluid.

Accordingly, a plurality of frequency components, i.e., the first frequency and the sum and difference frequencies of the first frequency and a 5 third frequency (a frequency as an integer multiple of the second frequency) are generated in the interelectrode electromotive force. From two of the plurality of frequency components, an asymmetrical exciting characteristic parameter (amplitude ratio or 10 phase difference) can be obtained, which depends on the flow rate of the fluid and does not depend on the variation in delay of the magnetic field with respect to the exciting current or the shift of the amplitude of the magnetic field.

15 When this asymmetrical exciting characteristic parameter is used, a flow rate can be calculated while quickly and automatically canceling a flow rate measurement error due to the variation in delay of the magnetic field with respect to the exciting current or 20 the shift of the amplitude of the magnetic field.

In addition, since in-phase component noise can be removed, the rectangular wave exciting method need not be used. Since the sine wave exciting method can be used, high-frequency excitation can be executed. 25 As a result, the flow rate can be accurately measured.